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Flight Evaluation of the CTAS Descent Advisor Trajectory Prediction

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1. Background

Since 1989, NASA's Langley Research Center and Ames Research Center have cooperated in investigating issues relating to application of air traffic control (ATC) automation. The particular system of interest is the Center TRACON Automation System (CTAS) [1,2], a ground-based system for automated management and control of terminal area air traffic which was developed by NASA Ames. The goal of the joint, multi-year effort is to explore issues relating to integration of the automation with airborne flight management systems (FMS).

Two simulator studies [3,4] between Langley and Ames evaluated the interaction that could be achieved between an airborne and a ground-based 4-dimensional (4-D) system, with a potential payoff of increased capacity and efficiency of terminal-area operations. The latter study indicated the potential for successful incorporation of a profile negotiation process between a 4-D FMS-equipped airplane and a time-based ATC system (CTAS). This process allowed the airplane to remain as close to its preferred trajectory while still satisfying ATC separation requirements.

In 1992 NASA Ames began conducting operational tests of the Descent Advisor (DA) portion of CTAS, which computes conflict-free 4-D descent profiles for all arriving aircraft, and operates within an area of approximately 200 nmi surrounding an airport. With an operational version of DA in the field, it was recognized that Langley's Transport Systems Research Vehicle (TSRV) could be used for actual flight test verification of the CTAS trajectory prediction capabilities. The TSRV is a modified Boeing 737-100 airplane equipped with a Research Flight Deck (RFD) situated behind the Forward Flight Deck (FFD). The RFD is equipped with electronic displays for all flight instruments and a flight management system. The FFD has conventional instrumentation and no FMS.

The first CTAS/TSRV flight test was conducted in 1992 at Denver Stapleton International Airport, where CTAS was implemented in a test mode. Arrivals into Denver are routed through one of four "corner post" arrival gates. For the flight test, the northeast arrival fix (KEANN) was used as the metering fix at which the arrival times were computed. The trajectories generated for these arrivals were straight segments with no turns, and the TSRV was flown using both flight path constrained and idle thrust descent procedures. Results indicated that the airplane could achieve arrival time accuracy within the 20-second design goal associated with DA. A remaining question was whether arrival time could still be met with a trajectory that contained turns, and with the different levels of FMS capabilities that currently exist. These were two of the primary factors to be investigated in the following flight test.

This paper describes that follow-on flight test conducted in September, 1994. The following section describes the test protocol, including the test matrix, equipment, and procedure. Following that is the section which describes collection of the weather, trajectory, and aircraft data. The fourth section summarizes the test results, including weather conditions encountered during the test days, and presents some arrival time summaries. The final section presents some concluding remarks about the test.

2. Test Protocol

This section describes the test protocol used, including the test matrix of runs, equipment used, ATC interaction, and the actual test procedure.

2.1 Test Matrix

There were two variables in this test: descent speed and level of FMS automation and procedures used on the airplane. Four different levels of FMS automation were chosen to represent a cross-section of current equipment being used. These levels were simulated by restricting the FMS on the TSRV at various levels, as summarized below.

A) no FMS - the FMS on board the research flight deck of the TSRV was used to compute a vertical descent profile and record the trajectory information generated, but the runs were actually flown from the front cockpit, which is not FMS-equipped. The pilots flying in the front cockpit were not given any information generated in the RFD FMS, but were told what the descent speed and top of descent for that run would be. The top-of-descent (TOD, the location along the horizontal path at which the descent is initiated) used in this case was the one generated by the CTAS DA, not the one generated by the FMS. The pilots had also been previously briefed

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on the procedures and speeds to be used in the test. The lateral path was flown using conventional VOR guidance.

B) full FMS - the FMS was used in full 3D mode to compute and then follow a lateral (LNAV) and vertical (VNAV) trajectory at the given descent airspeed. The descent was initiated at the TOD point computed by the FMS. A CTAS DA top-of-descent point was also computed, but was not used by the TSRV.

C) FMS with CTAS TOD - For these runs, complete LNAV and VNAV paths were generated by the FMS and flown as indicated, except that the descent was initiated at the DA TOD, rather than the FMS TOD. For descents prior to the FMS TOD, a shallow descent of approximately 1000 feet per minute was maintained until the VNAV path was intercepted. Descents initiated after the FMS TOD required speed brake to steepen the descent and intercept the VNAV path at the desired descent speed.

D) FMS LNAV with range/altitude arc - the FMS was used to compute and follow a lateral path. Descent was initiated at the CTAS TOD point, a range/altitude arc was used to target the proper crossing altitude at the metering fix, and thrust or speed brake used to maintain the desired descent speed. The range/altitude arc (Fig. 1) normally indicates the straight-line range at which a pre-selected altitude will be reached; for this experiment it was modified (labeled 'MCP / LNAV altitude mark' in Fig. 1) so that it showed the range along the computed horizontal path, even if that path is curved.

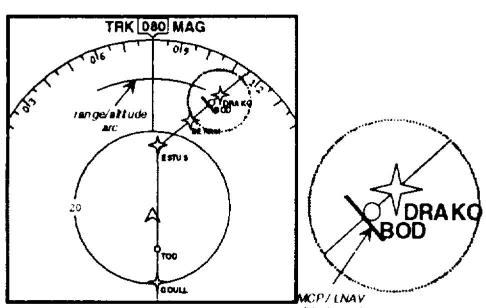

Fig. 1. TSRV navigation display with range/altitude arc.

Each of the four FMS configurations was flown at three different airspeeds, which represented a nominal, slow, and fast descent for this airplane. Cruise Mach / descent speeds were as follows:

1) 0.72 / 280 kts; nominal descent speed
2) 0.76 / 240 kts; slow descent speed
3) 0.76 / 320 kts; fast descent speed

Two repetitions of this matrix were completed, for a total of 24 test runs.

2.2. Equipment

The primary equipment used for this test consisted of the CTAS workstation on the ground at Denver Air Route Traffic Control Center (ARTCC), and the TSRV test aircraft operating in the Denver terminal area, with a radio link between the two.

The CTAS configuration consisted of two workstations operating a test version of the CTAS DA software. The workstations are located in the Traffic Management Unit (TMU) at Denver Center. A total of three people were located at the CTAS station during the flight test. Two of the people were operating the system and recording parameters such as initial conditions, top-of-descent location, and weather data. The third person acted as liaison between the NASA test and the Denver Center, ensuring that the test did not infringe on the traffic situation in any way that might produce delays for other aircraft, since the nature of the test was such that multiple approaches were required by the TSRV.

The TSRV was equipped with its normal suite of sensors and data recording, plus the capability to record trajectory data from the FMS. The FMS was also modified to have full 3-D navigation capability, similar in functionality to the B737-400 generation of flight management system.

All test flights were conducted within the Denver Center airspace. The TSRV was operated out of a fixed base located at the airport, and could be at the initial test point within one-half hour after take-off. Previous to the test, NASA personnel had met with representatives from Denver Center to brief them on the proposed procedures to be used by the NASA team, and to determine the best way for handling the TSRV's anticipated routing.

The test route used (shown in Fig. 2) was along the eastbound arrival route to the northwest arrival gate (DRAKO). The initial point (IP1) for the matrix test runs was at the Hayden (CHE) VOR. A second route is also shown in Fig. 2, beginning at the second initial point (IP2), which is inside the LYMIN fix, southbound to join up with the arrival traffic inbound to the KEANN metering fix. This second route was used to obtain additional weather data with the TSRV from a different quadrant, but runs conducted along this route were not used to complete the test matrix.

The desired mode of operation was for the TSRV to conduct multiple approaches between the starting point of the test runs and the metering fix, breaking off the approach after each arrival at the metering fix to return to the initial point for another run. Because of the airspace required for the TSRV to attain the initial test altitude, two different sector controllers, plus the approach controller were involved in the operation (all of whom had previously been briefed on the test procedure).

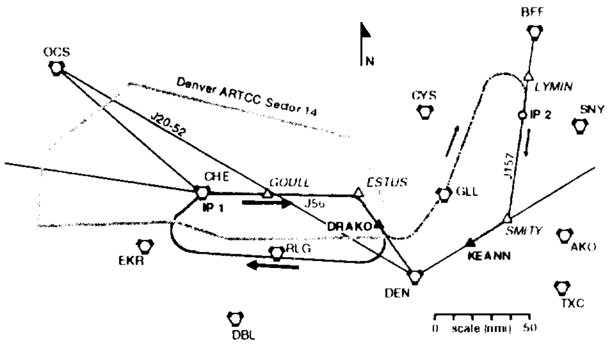

Fig. 2. Test routes used in CTAS/TSRV flight test

In order to improve the chances for the TSRV to conduct several descents in a row, the TSRV flights were chosen to start at times of anticipated low levels of traffic. The indicated sector controllers were briefed that they would be handling the NASA test airplane. During the actual TSRV flights, the site coordinator was present in the TMU area to confer with the CTAS test engineer, should any situations arise that might require a change in the test runs to be conducted, or termination of the TSRV flight.

2.3. Test Procedure

The day previous to each test flight, the Denver Center site manager coordinated with the NASA test directors to determine when were the anticipated low-traffic periods, for purposes of planning when the TSRV crew needed to be ready for preflighting and boarding the airplane. This was also re-checked on the day of the flight to ensure that nothing had changed in the schedule. The TSRV then departed with enough time to arrive at the initial point (IP1 or IP2, depending on whether the first run was to be a test matrix run or a weather run) at the beginning of the traffic lull. During the climb segment, the Langley test engineer on the TSRV coordinated via radio link with the CTAS engineer as to whether any changes had to be made to the previously agreed upon test runs for that flight.

The TSRV entered the arrival stream prior to IP1. Because this required a rather sharp turn, the speed data sent to the DA from the ATC host computer required some time to settle to its correct value before a valid TOD was computed and communicated to the TSRV. As indicated in the test matrix, in some cases the DA TOD value was used, and in others the FMS-computed TOD was used. In addition to the TOD an estimated time of arrival (ETA) was computed by the DA.

Following completion of each run, the TSRV either returned to IP1 for another test matrix run, was vectored to IP2 for initiation of a weather run, or landed, according to the scheduled run matrix for that flight.

3. Data Collection

There were three primary sets of data parameters that were collected during this test. These were: 1) airplane state variables, such as position, airspeed, ground speed, and altitude; 2) weather data, such as wind speed, wind direction, and air temperature; and 3) trajectory predictions from CTAS DA and the airplane FMS.

3.1 Airplane State Data

The TSRV sensors provided airplane state data, such as position (latitude/longitude), airspeed, ground speed, altitude, body angles, and accelerations. Most parameters were updated and recorded at a rate of 20Hz, but were averaged over 1 second in post-processing. Airplane tracking data was also obtained from the Automated Radar Terminal Systems (ARTS) host computer used by the ARTCC. The ARTS computer provided the data to the CTAS DA for computing trajectories for all the airplanes in the system. The ARTS tracking data consisted of position, altitude, track and ground speed.

3.2. Weather Data

Weather data was obtained from three independent sources: data obtained from the sensors aboard the TSRV airplane, data obtained by the National Center for Atmospheric Research (NCAR, from soundings, profilers, and models), and data that was provided by the National Oceanographic and Atmospheric Administration (NOAA) to CTAS for use in its trajectory synthesis algorithms.

The TSRV was equipped with sensors to measure wind speed, wind direction, and temperature at the TSRV location. The data was sampled at 20 Hz in flight, and averaged over a one-second period in post-processing. The NCAR data was combined from several different sources, and recorded during the times of the TSRV flights. This provided a wider field of weather data than could be obtained by a single airplane. The NOAA data used by CTAS was a weather prediction in a grid-type format so that data could be obtained at any point within the field by interpolation. The NOAA weather model prediction was updated every three hours.

3.3. Trajectory Predictions

Trajectories were computed and recorded by both the TSRV FMS and the CTAS DA. Both sources of trajectory predictions provided point-to-point trajectories (horizontal and vertical) for each descent, including a top-of-descent locations and estimated time of arrival at the metering fix.

4. Test Results

4.1. Weather Summary

The weather conditions for the first four flight test days were similar. On the fifth test day, it was predicted that a cold front would move through the area at mid-afternoon, bringing with it colder temperatures and precipitation. However, it was anticipated that the TSRV would be able to complete a number of runs before the weather deteriorated and began causing delays. Three test runs were completed before the TSRV was required to land.

Wind conditions changed significantly after the frontal passage. Previous to that, the wind speeds aloft were approximately 40-60 knots, as shown in Fig. 3 (labeled as F729). After the front passed through, the winds aloft increased to over 80 knots (labeled F732 in Fig. 3).

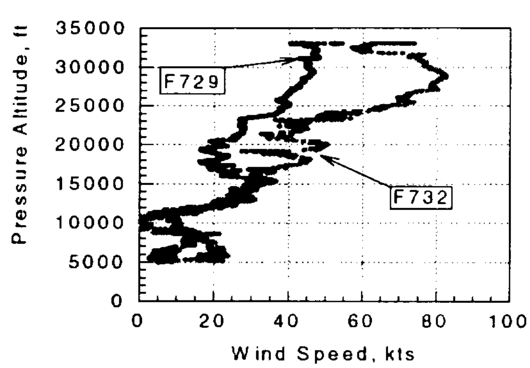

Fig. 3. Sample wind speed profiles from two flight days.

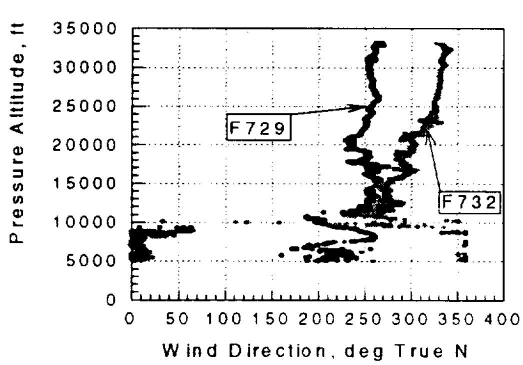

Fig. 4. Sample wind direction profiles from two flight days.

Wind direction shifted from west before the front to predominantly from the north after the front passed, as shown in Fig. 4.

A typical temperature profile for one of the first flight days had a higher than standard lapse rate (-50°C at 33,000 feet to 20°C at the ground). After the cold front passage, the lapse rate above 15,000 ft was similar to the previous days, but closer to standard below 15,000 ft, with temperatures of about 5 °C at the ground.

4.2. TSRV Arrival Time Results

A key measure of CTAS DA trajectory prediction performance is the arrival time accuracy achieved at the metering fix. TSRV flight data was compared to the CTAS and FMS trajectory predictions to determine how well each performed the task of estimating arrival time and to identify key errors in these predictions.

Early in the data analysis, systematic errors were discovered in the CTAS trajectory predictions which prevented a direct comparison of measured versus predicted arrival time. A change to the ATC Host computer radar tracking coordinate system, which was not implemented in the experimental CTAS software, resulted in an error of approximately 1.5 nautical miles in aircraft position. In order to eliminate this error from the analysis, the actual aircraft position was mapped to the old CTAS coordinate system and relative flight times for trajectory segments were computed. The FMS predictions were similarly adjusted to give a meaningful comparison.

The following table provides a summary of the arrival time errors computed in this manner as a function of FMS automation level used by the TSRV.

Automation Level	FMS prediction	CTAS prediction
All	8.8 ± 10.5	-2.3 ± 12.5
non-FMS	16.8 ± 9.4	1.7 ± 10.0
FMS-VNAV	4.9 ± 9.4	-6.3 ± 12.4
Nav ARC	9.1 ± 10.7	2.3 ± 13.8

Table 1. Arrival time errors (mean ± sdev in seconds) for both FMS and CTAS predicted trajectories.

In general, the arrival time errors were consistent with expectations and fell within the desired level of ± 20 seconds. Close analysis of individual trajectories, and the individual modeling parameters used to compute the trajectories, provided further insight in to the arrival time results.

The level of error in winds aloft modeling for the CTAS predictions was significantly worse than expected. Cruise wind errors averaged 12 knots with a standard deviation of 20 knots. On the flight which experienced the frontal passage, flight #732, cruise wind errors of more than 50 knots were observed. The geometry of the arrival trajectory, which resulted in predominately crosswind errors for the CTAS predictions, masked the modeling effect on arrival time. In fact, the arrival time error based on the FMS prediction, which used measured wind information, was greater than the time error based on the CTAS prediction, which had 50 knot wind modeling errors. Different arrival geometries would have resulted in significantly greater time errors (60 seconds or more).

The only significant factor directly applicable to the level of FMS automation was found to be the horizontal path distance flown using FFD (non-FMS) VOR guidance. Path distances averaged about 1.6 nautical miles longer than predicted due to the consistent overshoot of the turn inbound to DRAKO. This contributed approximately 13 seconds of delay to the arrival time error. The time error differences due to other levels of FMS automation were negligible in this test.

An additional factor observed in this test, which was not included in the arrival time analysis, was a systematic lag in the ATC radar-tracked location of the airplane compared to its actual location. Comparison of the flight data with the ARTS tracking data (as provided to CTAS) revealed an average lag of approximately 7 seconds with a standard deviation of about 3 seconds.

5. Concluding Remarks

Flight evaluation of the CTAS Descent Advisor under actual field conditions has provided valuable insight and verification of the CTAS trajectory prediction process. Although the arrival times were close for the DA and TSRV during most of the runs in this flight test, there remain some unresolved issues that could affect the overall performance of the system in an operational environment.

Improper modeling of the weather conditions, in particular the wind data, could produce significant error in predicted arrival times. Data from this and the previous flight test indicate that current weather products may not be adequate. Further work is needed to ensure a consistent source of reliable and accurate weather data is available.

The quality of airplane performance models and differences in trajectory generation techniques used by CTAS are not as critical. As long as the airplane follows the CTAS descent speed schedule, arrival time errors will be small. Errors in performance models, however, directly affect TOD calculation and influence the ability to use aircraft FMS automation to track the desired descent speeds. Performance modeling errors of nearly 10 percent were encountered in the flight tests without an adverse affect on trajectory following.

A final issue relates to operational procedures and the robustness of the CTAS system when it comes to handling situations that are different from the assumptions made in its trajectory prediction. In this test, the procedures used were specific for each level of FMS automation simulated. In the operational world, each airline, each airplane type (or FMS manufacturer), and potentially individual pilots, may have different procedures for executing any given maneuver. These differences must be understood and common procedures developed which provide a reasonable adherence to the CTAS trajectory predictions.

6. References

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